# A PROCESS FOR CONVERTING A LIQUID FEED MATERIAL INTO A VAPOR PHASE PRODUCT

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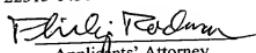
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## A PROCESS FOR CONVERTING A LIQUID FEED MATERIAL INTO A VAPOR PHASE PRODUCT

### FIELD OF INVENTION

5          A process for converting a liquid feed material into a vapor phase product using a cross-flow fluid bed.

### BACKGROUND OF THE INVENTION

10          Many industrial processes rely on fluidized beds as a means of contacting a solid and a fluid. The large surface area associated with the fluidized solids can lead to increased rates of mass and heat transfer when compared to competing alternatives. This is particularly important when applied to industrial chemical reactions. In one general

15   application the fluid bed is used to contact a liquid reactant phase with the fluidized solid particles; the particles provide catalytic or thermal benefits that allow the reactions to proceed. A number of such processes are used in the processing of hydrocarbons. Two commercial examples of this type of process are fluid catalytic cracking and fluid coking.

20          Upgrading is a general classification for processes used by refiners to improve the quality of heavy oils or the heavy fraction of crude oils. The word "residuum" is often used to describe the non-distillable fraction of an oil that boils above about 530°-565° C. Crude oils are usually referred to as heavy when they contain a significant fraction of residuum or "heavy" material. Fluidized beds offer many advantages when applied to upgrading process.

25          In a typical thermal upgrading process, or thermal conversion process, the solids do not play a catalytic role. Rather, activation energies are overcome solely through the application of heat, converting the feed stock into more valuable products. In these processes, the fluidized bed of solids provides the heat required for the conversion

30   reactions: the liquid hydrocarbon feed is applied to the hot solids where it reacts to form the products of the process. The reactions involved in the conversion of the feed to products are often referred to as cracking and coking reactions.

Ultimately, if enough reaction time is provided, the initial liquid feed will react completely to form final products that are either gases or solids at process conditions. The products of most interest are generally the portion of the gases formed in the process that can be condensed to liquids at ambient conditions. These are herein referred to as "liquid products", and in most cases represent the most valuable products of the thermal upgrading process. The solid product of the process is referred to as coke, and the portion of the gasses that are not condensable are referred to as non-condensable gasses.

At intermediate reaction times a liquid phase is present in the reactor. During this period, before the chemical conversion has gone to completion, there is an opportunity to affect the final outcome of the process. In any commercial process, the goal is to maximize the value of the products created from the feed, which usually equates to maximizing the quality and yield of the liquid products. As a result, through sound process design, the final amount and quality of the liquid products can be increased. Some examples of fluidized bed processes that have attempted to do this are fluid coking, riser coking and LR coking.

Based on research and upgrader operating experience available in the public domain, the following opinions have emerged regarding the attributes of an ideal thermal upgrading process:

1.    molecules in the feed of a quality acceptable to a conventional refinery should not be subjected to the severe thermal conditions associated with cracking reactions. Partially condensed polynuclear aromatics present in the feed material have been shown to produce coke through recombination reactions if subjected to thermal conversion conditions. Liquid yields can be improved if this fraction is removed prior to treatment. While somewhat subjective, based upon current wisdom the line of demarcation is approximately associated with molecules containing 3-4 aromatic rings;

2.    a reduction in temperature in the liquid phase will generally reduce the rates of reaction in the liquid phase, while having little effect on the rates of mass transfer. This will provide additional time in which to recover the reaction

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products before recombination reactions convert these molecules into coke precursors. As a result, liquid yields may increase with a reduction in temperature; and

3.     a reduction in temperature in the gas phase will increase liquid yields by decreasing overcracking of the products. Overcracking is the continued degradation of gas phase products while they remain at reaction temperatures. Overcracking converts liquid products into non-condensable gasses. Reducing overcracking by reducing reactor temperature can increase liquid yields and improve product quality. A reduction in the residence time of the gaseous products in the reactor will have a similar effect.

With these concepts in mind, an ideal series of events associated with a thermal upgrading process involving a bed of fluidized solids may be described as follows:

1.     liquid feed comes into contact with the fluidized solid particles;

2.     the fraction of the liquid feed containing molecules with less than 3-4 aromatic rings are flashed off and collected as product before significant cracking of this fraction has occurred;

3.     the molecules remaining in the liquid phase on the fluidized solids begin to thermally react;

4.     products of the thermal reaction that evolve as vapor from the surface of the fluid bed particles are swept away by the fluidizing gas, and are quenched before subsequent reactions (i.e. overcracking) can take place; and

5.     the residual liquid remaining on the fluid bed particles is provided with exactly the residence time required at reactor conditions to form a dry solid, with complete product evolution.

Fluid coking is a commercial thermal upgrading process which can be used to illustrate many of the concepts introduced above. The fluid coking process uses a bubbling

fluidized bed of solid particles. This type of fluidized bed resembles a boiling liquid. In the fluid coking process, hot solids enter the reactor in the freeboard region, above the surface of the fluid bed. Solid withdrawal occurs at the bottom of the reactor.

5          Feed is sprayed into the fluid bed at several different elevations where it coats the fluidized solid particles. The nature of solids mixing in bubbling fluidized beds leads to the condition that solids within the feed zone are generally well mixed. Before exiting the reactor, the solids pass through a stripping zone that is designed to lengthen the time that the liquid feed spends in the reactor. The additional residence time provided to the solids in the
10        stripping section, together with stripping steam, allows for the recovery of additional product from the liquid feed coating the surface of the fluidized solids.

          Because of the well mixed characteristics of the solids in the fluid coker, the residence time distribution (RTD) of the fluidized solids, and of the associated reacting liquid
15        feed that they carry, is very broad: the amount of time that solids and liquid feed spend in the reactor shows a large amount of variation. A common model used to describe systems that are very well mixed is a continuous stirred tank reactor (CSTR). The CSTR model describes the extreme case of a perfectly mixed system. The RTD of the solids in a fluid coker approaches that of a CSTR. As a result, some of the solids will short circuit to the exit of the reactor, while
20        others will spend a very long time at reactor conditions.

          The stripping zone of the fluid coker is designed to produce a solids RTD that is closer to plug-flow. The plug-flow model represents the opposite extreme of the CSTR model. In the plug-flow model, the RTD has one unique value, so all of the solids spend the
25        same amount of time in the reactor.

          Having good control over the RTD of the fluidized solids, and of the liquid feed that they carry, is important, and there are many advantages to operating with a RTD that approaches plug-flow. With a solids RTD approaching that of a CSTR, it is necessary to
30        tailor the designed solids holdup of the reactor to the portion of the solids that exit the reactor first. If the reactor hold-up is not designed to limit the short-circuiting of solids then liquid feed will be lost because it has not remained in the reactor for a sufficient amount of time to react to completion.

To reduce these losses, the reactor must be made larger or the solids throughput must be reduced. The breadth of the RTD in a CSTR results in a larger reactor with limited throughput.

5       Because all of the solids spend the same amount of time in a plug-flow reactor, the reactor design does not have to consider the short-circuiting of solids and the resulting losses of unreacted liquid feed. This allows for a physically smaller reactor with a potentially greater capacity.

10      It is noted that for the purposes of the above discussion, a flexi-coking reactor and process differs little from a fluid coking reactor and process.

In addition to limitations due to the RTD of the solids in a fluid coker, the gas phase dynamics associated with bubbling fluidized beds leads to a very broad gas phase RTD
15  in a fluid coker. Practical considerations associated with the design of fluid coking reactors require that significant bed depth be used in combination with increasing reactor diameter to provide the design solids holdup. The increased bed height along with the naturally broad gas RTD associated with bubbling beds results in long vapor phase residence times, which can result in the loss of product value through overcracking.

20      Various reactor configurations and processes have been devised that attempt to incorporate the idealized processing steps outlined above with better control over the RTD of both the gas phase and the solids phase, as compared with fluid coking. One such process is the riser (or transfer line) coking process. A second such process is the LR coking process,
25  which is described in U.S. Patent No. 5,658,455 (Hammond et al), U.S. Patent No. 5,714,056 (Hammond et al) and U.S. Patent No. 5,919,352 (Serrand et al).

A riser coking process relies on a fluidized bed, but operates at a much higher fluid velocity than a fluid coking process so that most of the solids are carried by the moving
30  fluid. This is typically referred to as fast-fluidization or dilute-phase transport, and provides significant differences in gas and solid phase mixing when compared to a bubbling fluidized bed. In this type of reactor, the solid carrier is sprayed with feed at one end of the riser or pipe, and transported to the opposite end of the pipe at a velocity equal to the velocity of the gas phase less the slip velocity between the two phases. The advantage of this design

is that all of the solids are carried through the bed at similar velocities. This results in a solid phase RTD that approaches plug-flow. The gas phase mixing dynamics are similar to those of the solids: gas phase mixing also approaches that of a plug-flow reactor.

5          The narrow RTD of both the solid phase and the gas phase could potentially allow for improvements over fluid coking, but the method of fluidization results in a coupling between the RTD of the solid phase and the RTD of the gas phase. This is because the velocity of the gas and solid phases differ only by the slip velocity, which is small relative to the average velocity. Since the required residence times for the

10    gas and solid phases are very different one must be compromised.

          The LR coking process incorporates a short gas phase residence time with an initial preflash to allow valuable molecules to be collected with minimal exposure to reaction conditions. In the LR coking process, solids are conveyed mechanically, which allows for an

15    independent solids residence time. Mechanical limitations do not allow for a sufficiently long liquid phase reaction time at design feed rates. To compensate for a relatively short liquid phase reaction time, the reaction rate in the LR coking process is increased by increasing the reaction temperature, a move which is in direct contradiction to the idealized conversion process described above. As a result of the increased temperature, conjugated olefins may be

20    formed in the gas phase by overcracking, which can lead to unmanageable fouling problems in the overhead system.

SUMMARY OF THE INVENTION

25          The present invention is directed at a process for converting a liquid feed material into a vapor phase product using a cross-flow fluidized bed. The present invention is also directed at an apparatus comprising a cross flow fluid bed reactor.

          The liquid feed material may be any suitable material. The liquid feed material

30    may be comprised of a single substance or may be comprised of a plurality of substances. The term "liquid feed material" as used herein means that the material is or behaves substantially as a liquid phase immediately before being subjected to the conversion process. As a result, the liquid feed material may be comprised of a suitable material which is substantially in a liquid phase at the particular temperature at which it is introduced to the conversion process.

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Preferably the liquid feed material is comprised of a liquid hydrocarbon. More preferably, the liquid feed material is comprised of a heavy hydrocarbon. For the purposes of the within description, a "heavy" hydrocarbon is a hydrocarbon which has a boiling point above about 530 ° Celsius. The liquid feed material therefore preferably includes at least some amount of hydrocarbon having a boiling point which is above about 530 ° Celsius. More preferably, the heavy hydrocarbon is comprised of a heavy oil or a heavy fraction of a crude oil.

The vapor phase product may be comprised of a single product, or substance, or may be comprised of a plurality of products or substances. The term "vapor phase product" as used herein means that the product is or behaves as a vapor phase under the conditions of the conversion process, although the product may ultimately be condensable to a liquid phase or even a solid phase.

In one process aspect the invention is a process for converting a liquid feed material into a vapor phase product comprising the following steps:

(a)     providing a fluid bed comprising solid particles and a fluidizing medium, wherein the fluidizing medium is moving in a substantially vertical fluidizing direction and wherein the solid particles are at a conversion temperature which is suitable for facilitating the conversion of the liquid feed material to the vapor phase product;

(b)     moving the solid particles in a substantially horizontal solid transport direction from an upstream horizontal position to a downstream horizontal position;

(c)     introducing the liquid feed material to the fluid bed at a feed zone located between the upstream horizontal position and the downstream horizontal position in order to facilitate the conversion of the liquid feed material into the vapor phase product; and

(d)     collecting the vapor phase product.

The solid particles may be comprised of any solid material which may be fluidized sufficiently to satisfy the requirements of the invention. Preferably the solid particles are comprised substantially of Geldart Type A and/or Geldart Type B particles. The solid particles may also consist of or be comprised of an amount of a catalyst which is capable of facilitating or enhancing the conversion of the liquid feed material.

The solid particles are preferably moved in the solid transport direction at a rate which is significantly larger than a rate of mixing of the solid particles in the solid transport direction. In other words, the Peclet (Pe) number describing the movement of the solid particles is relatively large so that the movement of the solid particles in the solid transport direction approaches plug-flow.

The solid particles are preferably introduced to the fluid bed at or adjacent to the upstream horizontal position and are preferably collected in a solid collection apparatus located at or adjacent to the downstream horizontal position.

The solid particles are preferably regenerated for re-use after they have been collected. The step of regenerating the solid particles for re-use may be comprised of heating the solid particles, preferably to the conversion temperature. The solid particles may be heated in any suitable manner. For example, the solid particles may be heated in a gasifier or a burner. The gasifier or burner may use a product of the reactions of the process, such as coke, as a fuel source.

The fluidizing medium may be comprised of any suitable fluidizing gas or vapor. In preferred embodiments the fluidizing medium may be comprised of gas which is produced during the regeneration of the solid material.

The fluidizing medium is preferably introduced at a lower vertical position below the solid particles so that the fluidizing direction is substantially upward. The fluidizing medium and the vapor phase product are preferably collected at an upper vertical position above the solid particles. The vapor phase product and/or the fluidizing medium are preferably collected together in a vapor collection apparatus. The vapor phase product is preferably separated from the fluidizing medium and is preferably quenched to minimize further conversion and/or degradation of the vapor phase product.

The liquid feed material may be introduced to the fluid bed in any suitable manner. Preferably the liquid feed material is sprayed so that the liquid feed material contacts the solid particles as droplets. Preferably the liquid feed material is introduced into the fluid bed so that the liquid feed material penetrates the fluid bed, preferably as droplets.

The direction in which the liquid feed material is sprayed or otherwise introduced to the fluid bed may be any direction, but is preferably substantially perpendicular to the solid transport direction. In preferred embodiments the liquid feed material is introduced to the fluid bed in either a substantially vertical spraying direction or a substantially horizontal spraying direction. Where the direction is vertical, the direction is preferably opposite to the fluidizing direction.

The step of collecting the vapor phase product may be comprised of collecting the vapor phase product at a plurality of vapor phase product collection locations spaced horizontally between the upstream horizontal position and the downstream horizontal position. The vapor phase product may be collected at the vapor phase collection locations in a single vapor collection apparatus or a plurality of vapor collection apparatus. The vapor phase product may have a composition which varies amongst the vapor phase collection locations so that different compositions of vapor phase product can be collected at different locations.

The process may be further comprised of the step of collecting a vaporized fraction of the liquid feed material at a vapor phase collection location which is adjacent to the feed zone so that portions of the liquid feed material can be collected as vapor before undergoing significant conversion and/or degradation. The vaporized fraction of the liquid feed material may be collected in the vapor collection apparatus.

In a preferred process aspect of the invention, a fluidizing medium such as a gas is introduced into a reactor to fluidize a bed of solid particles such that the fluidizing medium is moving in a substantially vertical fluidizing direction. The solid particles are transported substantially horizontally in a solid transport direction from a solids inlet at an upstream horizontal position in the reactor to a solids outlet at a downstream horizontal position in the reactor, preferably but not necessarily by the force of gravity. As the solid particles move through the reactor they are contacted by a liquid feed material comprising a liquid

hydrocarbon. The liquid hydrocarbon is introduced into the reactor at a feed zone which is located downstream of the solids inlet. The solid particles are at a conversion temperature which facilitates the reaction of the liquid hydrocarbon to produce one or more upgraded hydrocarbon products as a vapor phase product. The vapor phase product is collected in a vapor collection apparatus, preferably with the fluidizing medium. The vapor phase product is preferably separated from the fluidizing medium and is preferably quenched in order to minimize further conversion and/or degradation of the vapor phase product. The solid particles are collected in a solid collection apparatus associated with the solids outlet and are preferably regenerated for re-use.

The selection and design of the solid particles, vapor collection system, freeboard and fluidizing mechanism may be made so that vapor phase residence time is short relative to competing technologies and so that the residence time distribution of the solid particles approaches plug-flow conditions despite significant evolution of product within the fluid bed. The invention permits relatively high ratios of solids to liquid feed, which aids in achieving lower reactor temperatures.

For example, whereas there are significant constraints on the flow of solid particles a single LR coking reactor can process, and whereas significant costs associated with LR coking require that the process adopt relatively low solids-to-oil ratios, a cross flow coking reactor can process a relatively large amount of solid particles. This feature allows the invention to employ higher solids-to-oil ratios than may be employed with some competing processes, such as the LR coking process.

Furthermore, whereas the LR coking process is forced to adopt a relatively high operating temperature to compensate for low solids-to-oil ratios, no similar requirement exists for the current invention. In the practice of the invention a relatively high solids-to-oil ratio is used with feed and product recovery zones that are staged such that solid particle residence times may be tightly controlled.

BRIEF DESCRIPTION OF DRAWINGS

Embodiments of the invention will now be described with reference to the accompanying drawings, in which:

Figure 1 is a schematic drawing of a cross-flow fluid bed reactor according to a preferred embodiment of the present invention.

5              Figure 2 is an alternate schematic drawing of a cross-flow fluid bed reactor according to a preferred embodiment of the present invention depicting spraying of the liquid feed material within the fluid bed.

DETAILED DESCRIPTION OF THE INVENTION

10             In general, the present invention relates to a process and apparatus for converting a liquid feed material into a vapor phase product. Preferably, the present invention relates to a process and apparatus for converting a heavy hydrocarbon feedstock material into value added reaction products. In a preferred embodiment the heavy hydrocarbon feedstock
15    material is comprised of heavy oil or a heavy fraction of a crude oil.

Referring to Figure 1 and Figure 2, the central process unit in the preferred embodiment of the invention is a cross-flow fluidized bed reactor (20). As in most fluidized bed processes, a fluidizing medium (22), preferably a gas, is introduced into the bottom of the
20    reactor base (24) and exits at the top of the reactor (20) so that the fluidizing medium (22) moves in a substantially vertical fluidizing direction (26).

The fluidizing medium (22) fluidizes solid particles (28) to produce a fluid bed (30). The solid particles (28) in the fluid bed (30) move in a substantially horizontal solid
25    transport direction (32) from a solids inlet (34) at an upstream horizontal position to a solids outlet (36) at a downstream horizontal position. The solid particles (28) are collected in a solid collection apparatus (38) which is associated with the solids outlet (36).

In the preferred embodiment, the solid particles (28) move in the solid transport
30    direction (32) substantially under the influence of gravity. In other words, no mechanical device or apparatus is used to move the solid particles (28).

A liquid feed material (40) is introduced into the reactor (20) at a feed inlet (42) which is located downstream of the solids inlet (34) so that the feed inlet (42) is between the solids inlet (34) and the solids outlet (36).

5      A vapor phase product (44) is collected in a vapor collection apparatus (46) which is located at an upper vertical position (48) above the solid particles (28) and the fluid bed (30). The vapor collection apparatus (46) includes a plurality of vapor phase product collection locations (50). The vapor phase product collection locations (46) are spaced horizontally between the solids inlet (34) and the solids outlet (36). A vaporized fraction (51)

10     of the liquid feed material (40) is also collected at one or more of the vapor phase product collection locations (50) adjacent to the feed inlet (42).

The fluidizing medium (22) is also collected in the vapor collection apparatus (46) with the vapor phase product (44) so that the fluidizing medium passes from a lower

15     vertical position (52) below the solid particles (28) to the vapor collection apparatus (46) at the upper vertical position (48). The vapor phase product (44) is subsequently separated from the fluidizing medium (22) and quenched in order to minimize further conversion and/or degradation of the vapor phase product (44).

20     A significant difference between the invention and a conventional fluid bed process is that the solid particles (28) in the fluid bed (30) move substantially perpendicularly to the gas phase in the fluid bed (30). Solid particles (28) enter at the solids inlet (34), flow along the length of the reactor (20), preferably under the influence of gravity, and are removed at the solids outlet (36). Since the solid particle (28) and fluidizing medium (22) flows are

25     generated by independent driving forces, the two are essentially independent. This provides for a significant increase in flexibility, which will be discussed in detail in the description that follows.

The process and apparatus of the invention can produce a solid particle RTD which approaches plug-flow, allowing for evolution of a vapor phase product (44) within the

30     fluid bed (30). The benefits accruing from this solid particle (28) RTD together with other benefits of the invention can be leveraged by a person skilled in the art to provide significant advantages over the prior art.

For example, it is well understood by individuals skilled in the art how to manipulate operating and design conditions such as increased solids-to-feed ratios and the ability to deliver feed in a more controlled and uniform fashion to enhance operability and yield at typical reaction temperatures. The hydrodynamics of the invention have been studied with cold flow physical models, using dimensional analysis to establish a tie to typical process operating conditions.

1.      Reactor

In the preferred embodiment, the reactor (20) is divided into a number of zones, each having a different function:

1.      solid feed zone (60)
2.      liquid feed zone (62)
3.      reaction zone (64)
4.      solid withdrawal zone (66)
5.      gas distribution zone (68)
6.      freeboard zone (70)

Figure 1 and Figure 2 both depict a schematic which illustrates these different zones of the reactor (20).

The reactor (20) may have any suitable shape. In preferred embodiments, the reactor (20) has a generally rectangular shape. The length of the reactor (20) is typically greater than its width. This design feature ensures the solid particles (28) are well mixed across the width of the reactor (20), and helps to maintain plug-flow characteristics in the moving solid phase. The impact of plug-flow on the characteristics of the process is described below.

Gas is introduced as a fluidizing medium (22) through a gas distributor (76) located on or adjacent to the bottom of the reactor (20). The gas distributor (76) can vary in complexity. Bubble cap and perforated plate designs have been tested, but any design capable of adequately fluidizing the solids is acceptable. The fluidization medium (22), along with any

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vapor phase product (44) generated by the reaction, will typically exit at the top of the reactor (20).

The height of the reactor (20) is designed to accommodate both the fluid bed (30) contained in the reactor (20) and the height required for solids disengagement in the freeboard zone (70), as discussed below.

To provide effective contact between the liquid feed material (40) and the solid particles (28) and to take advantage of high solids-to-feed ratios it will generally be desirable to provide an amount of solid particles (28) substantially in excess of what is required for the liquid feed zone (62). By staging several of the units depicted in Figure 1 in series, the bulk of the solid particles (28) will be contacted in a more uniform fashion, while reducing the solids handling requirements. To increase capacity, the width of the reactor (20) can be increased, an option not available in many commercial configurations.

2.      Solid Particle Characteristics

The solid particles (28) in the reactor (20) provide the surface area upon which the conversion reaction occurs. In addition, the solid particles (28) provide a heat source or sink for the reaction, depending upon whether the reaction is endothermic or exothermic. The most critical attribute of the solid particles (28) is that the solid particles (28) should fluidize sufficiently well to satisfy the requirements of the invention.

The solid particles (28) may optionally also provide a catalytic function for facilitating or enhancing the conversion reactions which occur in the reactor. For example, the solid particles (28) may consist of or be comprised of an amount of a catalyst which is capable of facilitating and/or enhancing the conversion reactions, such as a type Y zeolite or any other material which is suitable for use in catalytic cracking or similar processes.

Based on the Geldart classification (Kunni D. and Levenspiel, O. Fluidization Engineering 2ed. Butterworth-Heinemann 1991), the following two types of solid particles (28) may be suitable for the reactor (20):

1.  Geldart A type particle: aeratable particles or materials having small mean particles size (<40 microns) or low particle density (<1400 kg/m$^3$). Fluidized cracking catalyst is an example of this type of particle.

2.  Geldart B type particles: most particles of size 40 microns to 500 microns and density 1400 kg/m$^3$ to 4000 kg/m$^3$. Sand is an example of this type of particle.

These two particle types characterize the typical particles used in industrial fluid beds. When fluidized, they provide the positive characteristics that are most often associated with fluid bed reactors: uniform temperature, high rates of heat and mass transfer, and high specific surface area. In addition, Geldart A and B particles are generally sufficiently fluid to allow for smooth horizontal flow.

All remaining particles fall into either the Geldart C (cohesive powders) or Geldart D (large coarse particles) classifications and are not typically suitable for use in the process of the invention unless they make up a relatively small fraction of the solid particles (28), with the majority of the solid particles (28) being Geldart A and/or Geldart B.

Other factors to consider when choosing the solid particles (28) are the heat storage and transfer characteristics, attrition rates and cost.

3.  Bed Characteristics

The fluid bed (30) will preferably be operated in the bubbling bed regime or, in the case of Geldart A particles, may be operated in the smooth fluidization regime below the bubbling fluidization velocity but above the minimum fluidization velocity.

In the bubbling bed regime the fluid bed (30) resembles a boiling liquid with bubbles forming at the gas distributor (76), rising through the fluid bed (30) quickly then bursting at the surface of the fluid bed (30). For descriptive purposes the fluid bed (30) can be thought to have two phases:

1.  an emulsion phase containing both solids and gas; and
2.  a bubble phase containing primarily only gas.

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Gas exits the fluid bed (30) almost exclusively in the bubbles. Gas in the emulsion phase must therefore first enter the bubbles in order to exit the fluid bed (30). The transfer of gas between the bubbles and the emulsion can occur by diffusion in the fluid bed (30) or by mixing in the turbulent region in the vicinity of the gas distributor (76).

4.    Freeboard Zone

The freeboard zone (70) is the solids lean region of the reactor (20) above the surface of the fluid bed (30). Solids are ejected from the fluid bed (30) by the action of bubbles bursting at its surface. The freeboard zone (70) is required for the solid particles (28) to disengage from the gas so that they are not carried out of the reactor (20).

The optimum freeboard height is that which allows all of the solid particles (28) with terminal velocities greater than the superficial gas velocity to disengage. Extending the freeboard above this height will not reduce the solids carryover and will only add to the cost of the reactor (20) and to the residence time of the gas phase.

Even for a very large freeboard zone (70), solid particles (28) will be carried out of the reactor (20) because they have been entrained in the gas or because of large eruptions of bubbles at the surface of the fluid bed (30) which can potentially eject solid particles (28) to the roof of the reactor (20). If the downstream gas processing units can not tolerate the presence of solids then a unit must be installed to separate the solid particles (28) from the gas stream. Proven technologies, such as cyclones, will be sufficient for this purpose.

Reducing the height of the freeboard zone (70) will reduce the residence time of the gas phase, which will in turn limit the severity of the gas phase reactions. However, inadequate height of the freeboard zone (70) can result in an excessive amount of solids carryover, requiring larger solids handling units outside the reactor (20) to separate the solid particles (28) from the gas.

The optimum freeboard height will be dependent on the type of solid particles (28), the fluidization velocity and the effects of the liquid feed material (40) on the cohesive

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forces between the solid particles (28). The residence time distribution of the gas in the freeboard zone (70) has been shown to be substantially plug-flow.

5.     Fluidization Velocity

5

         The solid particles (28) are fluidized by the gas that enters through the gas distributor (76) at the reactor base (24). The velocity of the fluidizing medium (22) should be above the minimum fluidization velocity and preferably below the turbulent fluidization velocity of the solid particles (28). If the fluidizing medium (22) velocity is below the

10     minimum fluidization velocity of the solid particles (28), then the fluid bed (30) will not fluidize and the solid particles (28) will not flow across the fluid bed (30). At fluidization velocities larger than the turbulent fluidization velocity, the carryover of solid particles (28) will be too great for a solids handling system of a reasonable size.

15       The range of superficial gas velocities that would function in the fluid bed (30) for Geldart B and Geldart A particles is from approximately 0.01 m/s to 1 m/s. Where the liquid feed material (40) is viscous, a safety margin should be added to the operating fluidization velocity to manage agglomeration of the wet solid particles (28).

20       The fluidization velocity has an impact on many characteristics of the reactor (20). As the velocity is increased the gas phase residence time will decrease, but the concentration and height of solid particles (28) in the freeboard zone (70) will increase. Solid mixing also increases within the fluid bed (30) when the fluidization velocity is increased. This reduces the plug-flow nature of the solids flow, but increases the resistance of the fluid

25     bed (30) to defluidization, which is of concern when processing a viscous liquid feed material (40). All of these factors must be considered when choosing the fluidization velocity.

6.     Solids Throughput

30       Solid particles (28) are preferably fed into one end of the reactor (20) and withdrawn at the opposite end. The solid particles (28) preferably flow in a substantially horizontal solid transport direction (32). The fluidized solid particles (28) behave hydrodynamically like a continuous fluid and can be made to flow across the fluid bed (30) under the influence of gravity. This flow could be simply induced by the difference in bed

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depth caused by feeding the solid particles (28) into one end, or by tilting the reactor (20) in the direction of flow. Tilting the reactor (20) has the advantage of maintaining a more uniform fluid bed (30) depth and allows for greater solid particles (28) flowrates. In either case, the depth of the fluid bed (30) may optionally be maintained through the use of a weir (not shown) near the solids outlet (36).

The solids flux through the reactor (20) will likely be a primary factor in determining the capacity of the reactor (20) to accept the liquid feed material (40). This will be the case when the heat or surface area requirements of the reaction are limiting. If required, it is possible to increase the mass flow of solid particles (28) through the reactor (20) at a constant flux by increasing the cross-section of the fluid bed (30).

7.    Liquid Feed Delivery

In the preferred embodiment, the liquid feed material (40) is sprayed onto the fluid bed (30) using feed nozzles (78). The liquid feed zone (62) of the fluid bed (30) which is used to accept the atomized liquid feed material (40) is the zone immediately following the solid feed zone (60).

The feed system should maximize the distribution of liquid feed material (40) over the solid particles (28) that pass through the liquid feed zone (62). The optimum situation would be to have every droplet of feed hit and engulf a different solid particle (28). This would maximize the surface area over which the reaction occurs which reduces any mass transfer limitations.

To maximize the spread of liquid feed and minimize mass transfer limitations, the droplet size should preferably be less than or equal to the solid particle (28) size, which will allow the droplet to form a thin film over the solid particle (28). This will be limited by the wetting properties of the solid particles (28) and the liquid feed material (40). If the feed droplets are too large they can potentially cause the agglomeration of the solid particles (28) in the fluid bed (30), and if they are too small they may be entrained in the rising fluidizing medium (22).

The feed nozzles (78) are preferably oriented so that the liquid feed material (40) is sprayed in a spraying direction which is substantially perpendicular to the solid transport direction. For example, the feed nozzles (78) can be oriented vertically, pointing downward through the surface of the fluid bed (30). Alternatively, the feed nozzles (78) can be oriented horizontally, through the walls of the reactor (20) or in through the reactor base (24). There is an advantage to spraying the liquid feed material (40) into the lower portion of the fluid bed (30) since this is an area of good mixing between the solid particles (28) and the fluidizing medium (22). For any feed nozzle (78) orientation, the aim is to penetrate the fluid bed (30) with liquid feed material (40) without impacting the bottom or sides of the reactor (20).

8.    Bed Depth

A shallow fluid bed (30) has the advantages of reduced gas phase residence time, increased gas-solid contacting, reduced horizontal solids mixing and a reduced concentration of solid particles (28) in the freeboard zone (70). All of these effects will be advantageous for most of the reaction systems that will operate in the reactor (20).

The following two operational issues will influence the minimum depth of the fluid bed (30) in the reactor (20):

1.    the required solid particles (28) throughput; and
2.    the liquid feed material jet penetration.

The maximum solid particles (28) throughput is dependent upon the maximum horizontal solid particles (28) velocity and the fluid bed (30) cross-section perpendicular to the flow. While operating with a smaller fluid bed (30) depth can have many advantages (as discussed below), reducing the fluid bed (30) depth will reduce the solid particle (28) capacity of the reactor (20).

The feed nozzles (78) preferably deliver the liquid feed material (40) to the fluid bed (30) without creating liquid droplets of a size that will be entrained in the upward moving fluidizing medium (22). To accomplish this, adequate momentum is imparted to the feed droplets to allow some penetration of the liquid feed material (40) into the fluid bed (30).

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Where the liquid feed material (40) is sprayed vertically downward, the fluid bed (30) should be deep enough relative to the momentum imparted to the feed droplets so that the liquid feed material (40) does not impact on the base of the gas distributor (76). This limit on the fluid bed (30) depth can be avoided if the liquid feed material (40) is sprayed horizontally into the fluid bed (30). This will then place the constraint on the minimum bed width in order to avoid the liquid feed material (40) impacting upon the sides of the reactor (20). Through proper design, the feed delivery system can be engineered to provide the required performance.

9.    Temperature

The temperature of the reactor (20) will be dependent upon the requirements of the reaction. The temperature drop across the reactor (20) will be dependent on the heat requirements of the reaction and the heat capacity and mass flow of the solid particles (28). Proper control of the freeboard temperature may mitigate overhead fouling problems encountered by other processes.

10.    Pressure

Slight positive pressure (0.5-10 psig) is desirable in that there is expense involved with providing the fluidizing medium (22) which, at a constant superficial gas velocity, will decrease as the pressure is reduced. In addition, the rectangular shape of the reactor (20) in the preferred embodiment is less suited to pressure containment than cylindrical designs which again make low operating pressures desirable. Downstream gas processing requirements will likely set the lower boundary for system pressure.

11.    Process Advantages

Depending upon the specific design and implementation of the invention as set out above, the invention may provide some or all of the following advantages over prior art processes:

(a)    Approach to Plug-Flow of Solid Phase Residence Time Distribution

The assumption of plug-flow is an ideal case where every solid particle (28) has the same horizontal velocity. The solid particles (28) move along the length of the reactor (20) in uniform plugs that are well mixed in the radial direction. Since every solid particle (28) has the same horizontal velocity, there can be no mixing along the length of the reactor (20). In the process of the invention, the solids RTD approaches the plug-flow ideal since the bulk rate of solids flow along the length of the fluid bed (30) is much larger than the rate of solids mixing in the same direction. In engineering terms, this is equivalent to stating that the Peclet (Pe) number is relatively large.

The plug-flow characteristics of the solid particles (28) takes greater advantage of the reactor volume than a fluid bed which is well mixed. This is because the RTD of the solid particles (28) is much narrower than in a fluid bed reactor that is well mixed. This allows for many advantages all of which are related to the narrow RTD:

1.    greater capacity in a smaller reactor, thus reducing capital costs;

2.    larger ratio of dry particles (28) to liquid feed material (40), allowing more liquid feed material (40) to be added to the fluid bed (30) without risking agglomeration of the solid particles (28), a condition known as "bogging". In many cases, this allows the reactor (20) to be operated at lower temperatures, as more severe conditions are not required to address bogging issues; and

3.    reduced loss of liquid feed material (40) by preventing solid particles (28) from short circuiting through the reactor (20). In well mixed reactors, short circuiting of wetted solids force operation at higher reaction severity.

(b)    Flow Characteristics of the Gas Phase in the Freeboard Zone

The gas exiting the free surface of the fluid bed (30) has also been shown to exhibit substantially plug-flow characteristics, with relatively little mixing in the direction of flow. As a result, the time that the gas spends under reactor conditions is minimized, and subsequent reactions that can downgrade the vapor phase product (44) are minimized.

(c)    Substantial Decoupling of Gas and Solid Particles Residence Times

The cross-flow design allows the residence times of the solid particles (28) and the gas phase to be adjusted independently. The solid particles (28) residence time is set by the solid particle (28) bulk horizontal velocity and the reactor (20) length. The gas phase residence time is controlled primarily by the bed depth and the fluidization velocity. This allows for the independent optimization of the gas phase and the solid particles (28), and hence independent control of the reaction severities associated with the gas and liquid phases, offering a significant advantage over technologies based on dilute transport.

(d)    High Rate of Vertical Mixing in the Fluid Bed

The high rate of vertical solids mixing in the fluid bed (30) increases the efficiency with which the liquid feed material (40) is distributed throughout the solid particles (28). This attribute is dramatic when compared to other technologies that incorporate a moving bed of non-fluidized particles. The high rate of vertical mixing in the fluid bed (30) allows for a deeper fluid bed (30) as opposed to a non-fluidized bed which must be made shallow. Furthermore, the superior feed distribution has a positive impact on product formation in cases were mass transfer through the reacting liquid phase is in issue, as the liquid films thicknesses are kept to a minimum.

(e)    Amenability to Small Scale Field Applications

The process of the invention is well suited for either scale up or scale down. It may therefore be used either to process relatively large volumes of liquid feed material (40) or in field applications to process relatively small volumes of liquid feed material (40), such as on the order of 1000-10000 barrels per day.

(f)    Ability to Design Solids Holdup Without Affecting Vapor Phase Severity

When a viscous liquid feed material (40) is sprayed into a fluid bed (30), there is the danger that the solid particles (28) will agglomerate, and the fluid bed (30) will defluidize. This condition is referred to as "bogging". The tendency for bogging can be addressed by

increasing the amount of dry solid particles (28) onto which the liquid feed material (40) is introduced. This parameter is fixed during the design phase.

     With a well-mixed reactor, increased solid particle circulation necessitates increased reactor residence time to accommodate additional product short circuiting. Due to mechanical and other practical constraints, it is not typically possible to increase the reactor volume without increasing the reactor height. As a result, increasing solid particle circulation increases the gas phase residence time, and hence product losses through the increase in reactor severity. The invention does not suffer from these design issues, since solid particle (28) throughput can be increased at constant bed height by increasing the width of the reactor (20).

     Once a reactor is in operation, avoiding bogging in a conventional well-mixed fluid coker is usually accomplished by increasing severity, which ensures that the liquid quickly reacts to completion. This operating strategy can be undesirable for many reactions, as the products may be degraded to less valuable chemicals under the increased severity. The increased solid particles (28) to liquid feed material (40) ratio afforded by the invention allows for a lower operating temperature without bogging, thus reducing the degradation of products which typically results from increased process severity.

    (g)    Discrete Zones with Ability to Tailor Fluidizing Medium to These Zones

     Because feed zones and product recovery zones are distinct, fluidizing medium (22) rates and fluid bed (30) properties can be tailored to the requirements of the specific zones. For example, to manage bogging, more fluidizing medium (22) can be used in the liquid feed zone (62).

    (h)    Fluid Bed Volume Near Gas Entry Point is a Significant Fraction of Total Volume

     It has been shown that exchange of product vapour from emulsion to bubble phase is much better near the gas entry point of a fluid bed reactor than anywhere else in the bed. This region of the reactor is often termed the "grid zone". Since the proportion of the fluid bed (30) which is in the grid zone is higher in the reactor (20) of the invention than in typical prior art reactors, this provides an advantage to the quick evolution of the vapor phase product (44).

(i)     Vapor Phase Products Separated Spatially

Because of the plug-flow nature of the solid particles (28) and the liquid feed material (40) that they carry, the vapor phase products (44) of the reaction will be separated in space along the length of the reactor (20). This allows vapor phase product (44) streams generated at different locations along the length of the reactor (20) to be collected independently. Because of this, it may be possible to tailor the gas recovery system for different product flowrates and potentially different compositions.

The spatial separation of products combined with the independent and relatively short gas phase RTD may also enable portions of the liquid feed material (40) which can vaporize quickly upon entering the reactor (20) to do so, exit the reactor (20) and be collected and/or quenched before experiencing significant reaction and chemical change resulting in degradation to less desirable products.

12.     Application Case 1 - Application to the Upgrading of Heavy Oil

The following description describes a theoretical design of a specific application of the invention for the upgrading of a heavy oil, such as Athabasca bitumen. In this application, four reactor units are used in series (i.e. the solid particles (28) will flow from one reactor (20) into the next). Each unit has been designed to process feed at a rate of 250 bbl/day making the total capacity 1000 bbl/day. The design specifications and operating conditions for this application are listed in Table 1. The specifications listed in Table 1 are for a single reactor unit, and are based on an extensive piloting exercise designed for this purpose. The following is a brief explanation of the rationale behind the numbers in Table 1.

Table 1

Operating Condition and Design Ranges for a Single Reactor Unit

Specific to Bitumen Where the Goal is to Maximize Liquid Yield

|  | Suitable | Preferred | Optimal |
|---|---|---|---|
| Reactor Length | 3 m – 6 m | 4 m – 5 m | 4.2 m |
| Reactor Height | 1.2 m – 8 m | 2.5 m – 6 m | 3.5 m |
| Reactor Width | 0.5 m – 3 m | 0.75 m – 2 m | 0.75 m |

| Solid Particle Size | 50 microns – 800 microns | 50 microns – 500 microns | 250 microns |
|---|---|---|---|
| Bed Depth | 0.2 m – 3 m | 0.5 m – 2 m | 1 m |
| Freeboard Height | 1 m – 5 m | 2 m – 4 m | 2.5 m |
| Reaction Zone | 2.5 m – 3.5 m | 2.5 m – 4 m | 3.2 m |
| Feed Zone | 0.5 m – 1 m | 0.5 m – 1 m | 1 m |
| Superficial Fluidizing Gas Velocity | 0.1 m/s – 0.7 m/s | 0.2 m/s – 0.6 m/s | 0.45 m/s |
| Solids Bulk Horizontal Velocity | 0.02 m/s – 0.2 m/s | 0.05 m/s – 0.15 m/s | 0.1 m/s |
| Mean Reactor Temperature | 440° C – 580° C | 480° C-520° C | 485° C |

The solid particles (28) selected for this application are coke particles and/or sand particles with a preferred mean particle size of between about 50 and 500 microns. During operation a coke layer will form on the base particles.  The average coke layer is estimated to be between about 10 and 40 microns thick, which will increase both the mean and variance of the particle size distribution.  Smaller particles will also be formed by the attrition of larger particles.  A solids purge stream is preferably withdrawn in order to control the accumulation of heavy metals in the coke, since there is some evidence that heavy metals can catalyze dehydrogenation reactions which will reduce the value of the reaction products.

The freeboard height is preferably between about 2-4 m.  This may be larger than the optimal freeboard height of 2.5 m, but will ensure that solids carryover is kept to a minimum.

The fluidized bed depth for the bitumen feed is preferably between about 0.5 and 2 m.  This brings the total required reactor height to about 2.5-6 m.  The bed depth is set by considering the gas phase residence time while still maintaining a sufficient reactor (20) cross section for solid particles (28) throughput.

Due to the viscous nature of the liquid feed material (40) a preferred minimum fluidization velocity of about 0.2 m/s is provided to maintain proper fluidization.

5    In this application, the horizontal solid particle (28) velocity through the reactor (20) is preferably between about 0.05 and 0.15 m/s. This velocity is based on the heat and surface area requirements of the system. It may be necessary to tilt the fluid bed (30) in the direction of solids flow to achieve the required bulk horizontal velocity.

To produce the desired reaction, the minimum operating temperature of the
10    reactor (20) is preferably about 485° C. Solid feed temperatures to the reactor (20) are between about 490° C and about 510° C. A heat balance for the overall system indicates that the temperature drop across each reactor unit may be between about 12° C and about 30° C, making the mean reactor temperature range between about 475° C and about 504° C. This application of the invention operates at moderate pressures (between about 5 psig and about 16
15    psig).

A partial oxidation gasifier (not shown) may be used to provide heat to the reactor (20). This technology is readily available from a number of vendors. The solid particles (28) will be heated in this unit before they are returned to the main reactor unit. The
20    gasifier will use the coke that is formed in the reactor (20) as a fuel source, and the gas formed in the combustor will be used to fluidize the main reactor (20).

Most of the evolved vapor phase product (44), which may comprise more than one substance or product, will be generated in the emulsion phase of the fluid bed (30). Due to
25    the rapid vertical mixing of solid particles (28) the vapor phase products (44) will be formed at all heights within the fluid bed (30). Due to the fluid mechanics associated with the fluid bed (30), the gas contained in the emulsion phase of the fluid bed (30) will generally flow downwards, in opposition to the upward flow of gas in the bubble phase. Vapor phase products (44) will be transferred from the emulsion phase to the bubble phase mainly through
30    the mixing of the gas from these two phases in the grid zone of the reactor (20).

Reducing the height of the fluid bed (30) increases the portion of the fluid bed (30) occupied by the grid zone, and also reduces the time it takes for the evolved products to

reach the bottom of the fluid bed (30) and be mixed into the escaping bubbles. The bubbles can then rise to be collected in the vapor collection apparatus (46) at the top of the reactor (20).

The invention potentially provides economic advantages over competing fluid bed technologies that have well mixed solids and confounded gas and solid phase residence times. Where the desire is to maximize the yield of condensable overhead vapors, three main advantages are noted:

1.    reduced reactor operating temperatures. As discussed above, in a well mixed reactor, lower reactor temperatures increase the risk of bogging. This concern is managed in the invention through increased solids throughput, enabling lower operating temperatures and increased yields;

2.    decreased losses of unreacted product. A well mixed reactor will also result in the loss of unreacted feed, due to the residence time distribution of the solid particles. This effect is minimized in the invention; and

3.    decreased over-cracking of gaseous products. The relatively shallow bed used in the invention allows for a reduced gas phase residence time so that valuable products are not degraded due to high severities.

Points 1 and 2 above can potentially be addressed for a process incorporating a well mixed fluid bed reactor by making the reactor significantly larger. However, increasing the size of the reactor will significantly increase capital costs. In the current example, a well mixed reactor would require 16.5 times the solid particle holdup in order to ensure 95 % of the solid particles are retained for a sufficient amount of time for the reaction to go to completion. Furthermore, this apparent remedy will only serve to exacerbate the problem outlined in Point 3, offsetting any incremental benefit associated with the increased reactor size.

As a conservative estimate of incremental yields, the invention may have the capacity to increase the yield of condensable products by 2-3 %, on an absolute basis. This credit is conservative since it is based only on gains realized from reduced overcracking in the gas phase. No benefits are attributed to the positive impact reduced temperatures are expected to have on the liquid phase reactions. The magnitude of this increase in yield would be very

important, since yield increments on the order of 0.1 % are seen in industry as significant, and have formed the basis for major capital expenditures. As a result, the invention provides the additional benefit of making better use of the natural resource. This is also significant given environmental concerns that have received worldwide attention and general endorsement.

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